Contract NAS8-32390
DRD-MA-04

SYSTEMS DEFINITION STUDY FOR SHUTTLE DEMONSTRATION FLIGHTS OF LARGE SPACE STRUCTURES

volume 1
executive summary

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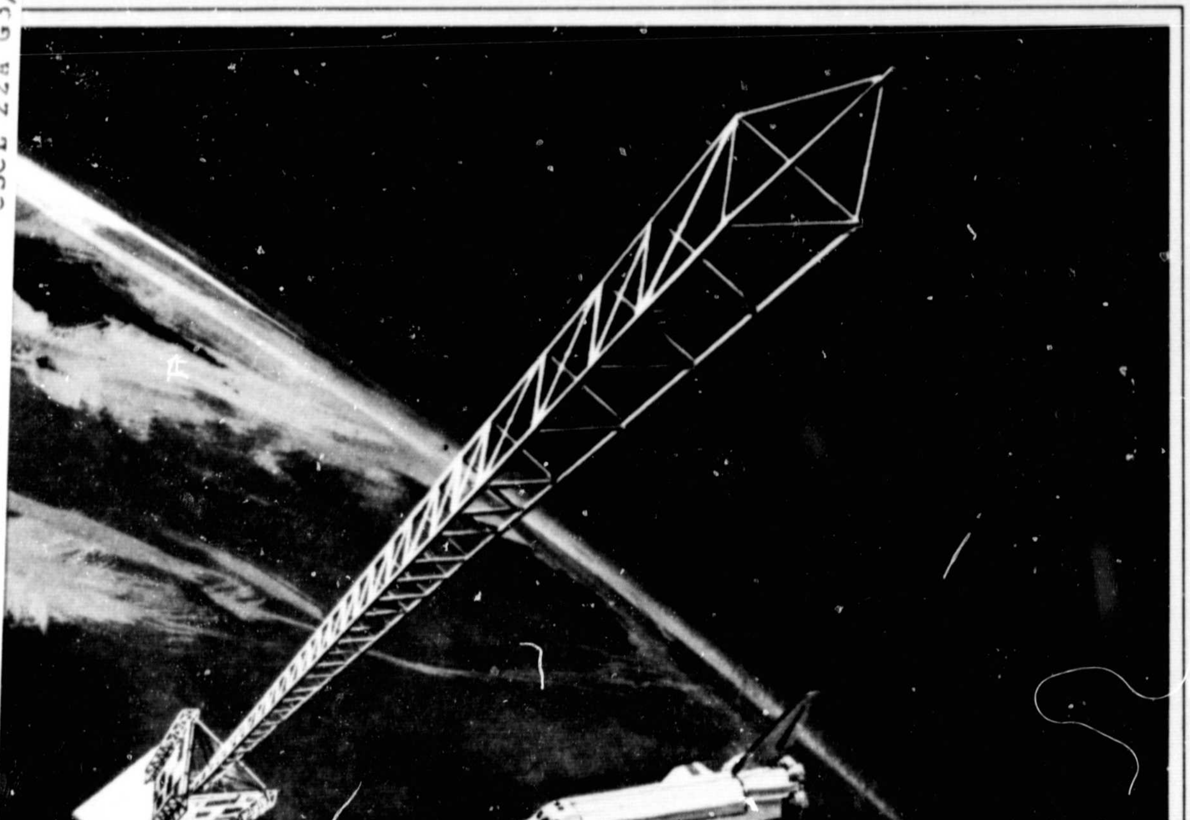

GRUMMAN AEROSPACE CORPORATION

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SYSTEMS DEFINITION STUDY FOR SHUTTLE DEMONSTRATION FLIGHTS OF LARGE SPACE STRUCTURES

volume 1
executive summary

prepared for
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

by
Grumman Aerospace Corporation
Bethpage, N.Y. 11714

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FOREWORD

This study was conducted for the Marshall Space Flight Center (MSFC) and directed by the Contracting Officer's Representative (COR), Mr. J. Harrison. The Grumman Aerospace Corporation's study manager was John Mockovciak, Jr.

This final report is presented in three volumes:

- Volume 1 - Executive Summary
- Volume 2 - Technical Report
- Volume 3 - Thermal Analyses
- Volume 3A - Thermal Analyses Appendix.

CONTENTS

ILLUSTRATIONS

1 - INTRODUCTION

Future utilization of space will involve new initiatives requiring large space structures (LSS) that can potentially serve a broad range of needs, including: communications, earth resources, radio astronomy, public service, and solar electric power systems.

The development of techniques for building large-area, low-density space structures, therefore, represents a new threshold in the continuing evolution and development of space technology. Launch vehicle payload and volume limitations dictate, basically, two approaches:

- Ground fabricated structures which are packaged and launched into orbit for deployment and assembly
- Space fabricated structures which are automatically manufactured in space from sheet-strip materials and assembled on-orbit.

Of the two alternatives, space fabrication allows structural materials to be packaged in a launch vehicle system with maximum possible density. Further, it allows the fabrication of "building block" structural elements for a wide spectrum of future large space structures.

An essential "stepping stone" in the development of LSS technology is a flight demonstration involving an Automated Beam Builder (ABB) and the Shuttle to establish that on-orbit manufacturing and assembly of large structures is feasible and practical. This study addressed the definition of this initial LSS demonstration mission.

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2 - STUDY OBJECTIVES AND SCOPE

A near-term objecgive of NASA's Large Space Structure Program is to develop the capability to package, transport, fabricate, assemble, and integrate large structures in orbit using the Shuttle Orbiter as a construction platform. In support of that goal, the initial phase of this study:

- Identified desireable LSS demonstration requirements and generated design concepts satisfying those needs, and
- Developed programmatic approaches, using an automated beam builder (AAB) and Shuttle capabilities, to perform an LSS flight demonstration in the 1983-1984 time-period.

The two candidate demonstration options developed during the initial study phase are illustrated in Fig. 2-1.

- Structural demonstrator - A simple concept which demonstrates a limited degree of on-orbit structural fabrication
- LSS Platform - A similar, but larger platform structure which demonstrates on-orbit fabrication and has user utility.

The free-flyer option of the LSS platform had its major cost associated with subsystem support functions. Hence, it was suggested that an existing or near-term subsystem support module (e.g., the 25 kW Power Module (PM)) be investigated as the potential "base" for an LSS platform. As Fig. 2-2 shows, the follow-on phase of this study addressed the development of free-flying LSS platform concepts utilizing a 25 kW PM, within which LSS applications were sought to provide a near-term relevance for the LSS demonstration mission. From the LSS applications identified, the latter phase of this study developed an LSS demonstration concept utilizing structural features relevant to space platforms.

In parallel with the concept development activities, supporting analyses related to aspects of LSS and one-meter beam applications have been investigated. These efforts have enlarged our fundamental understanding of LSS, in general, and have

been used to support the definition of the LSS demonstration mission and to assess the feasibility/practicability of other candidate LSS concepts, such as the gravity wave interferometer and pin-hole camera.

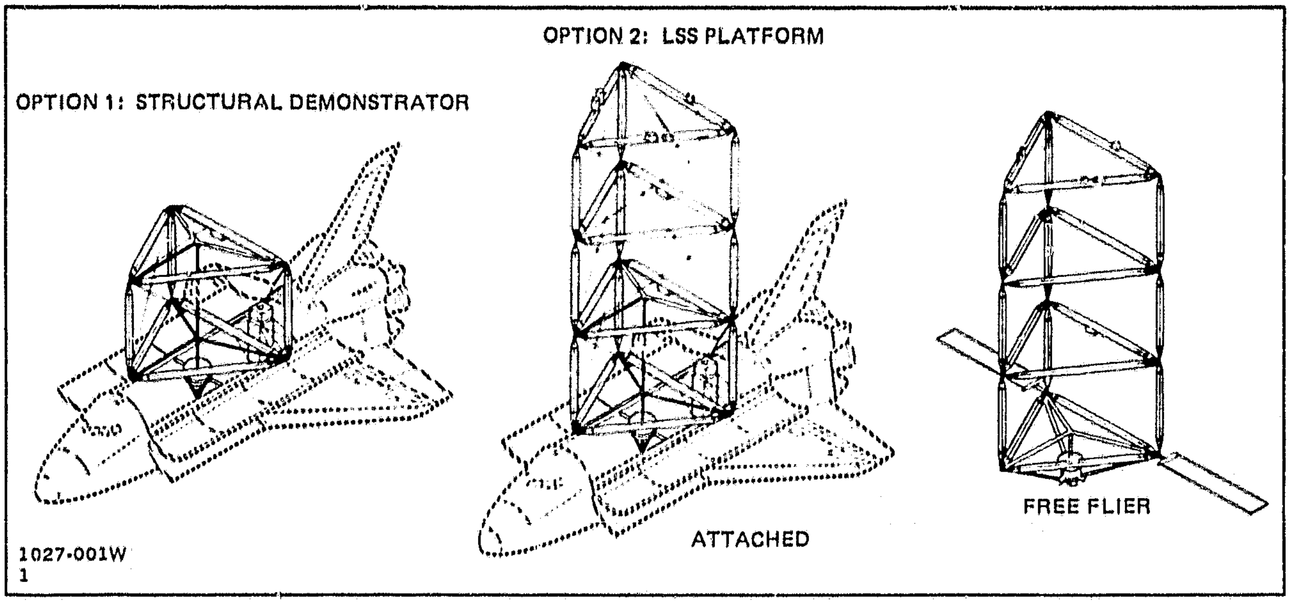

Fig. 2-1 Initial LSS Demonstration Options

PM/PLATFORM CONFIGURATION DEVELOPMENT

- DEVELOP FREE-FLYING LSS CONCEPTS UTILIZING 25 kW POWER MODULE
- IDENTIFY POTENTIAL LSS APPLICATIONS.

LSS DEMONSTRATION CONCEPT DEVELOPMENT

- ADAPT PM/PLATFORM LSS APPLICATIONS TO AN LSS CONCEPT FOR INITIAL STRUCTURAL DEMONSTRATION MISSION
- DEVELOP PROGRAMMATIC APPROACHES, USING AN AUTOMATED BEAM BUILDER AND SHUTTLE CAPABILITIES, TO PERFORM AN LSS DEMONSTRATION IN 1983-84 TIME PERIOD.

SUPPORTING ANALYSES

- STUDY RELATED ASPECTS OF LSS AND 1-METER BEAM APPLICATIONS
  - TRANSIENT THERMAL ANALYSIS OF 1-METER BEAM AND TRIBEAM STRUCTURE
  - CONSTRUCTION LIMITATIONS FROM SHUTTLE
  - DEMO PLATFORM INSTRUMENTATION APPROACHES.

LSS CONCEPTS EVALUATION

- ASSESS ALTERNATE LSS APPLICATIONS
  - GRAVITY WAVE INTERFEROMETER
  - PINHOLE CAMERA.

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Fig. 2-2 Follow-on Study Objectives

3 - SUMMARY

3.1 MAJOR FINDINGS AND CONCLUSIONS

3.1.1 LSS Concept Development

A LSS flight demonstration mission has been identified which will demonstrate on-orbit fabrication, assembly, and integration of a large structure, and also provide a user-oriented satellite platform in the process. As illustrated in Fig. 3-1, the satellite incorporates the two principal large structural elements found in Power Module/Platform concepts developed during this study. Namely, a segment of the Tribeam "strongback" related to an earth viewing platform, and a long stabilizing boom characteristic of the long booms providing inertial symmetry for solar/stellar and materials processing platforms.

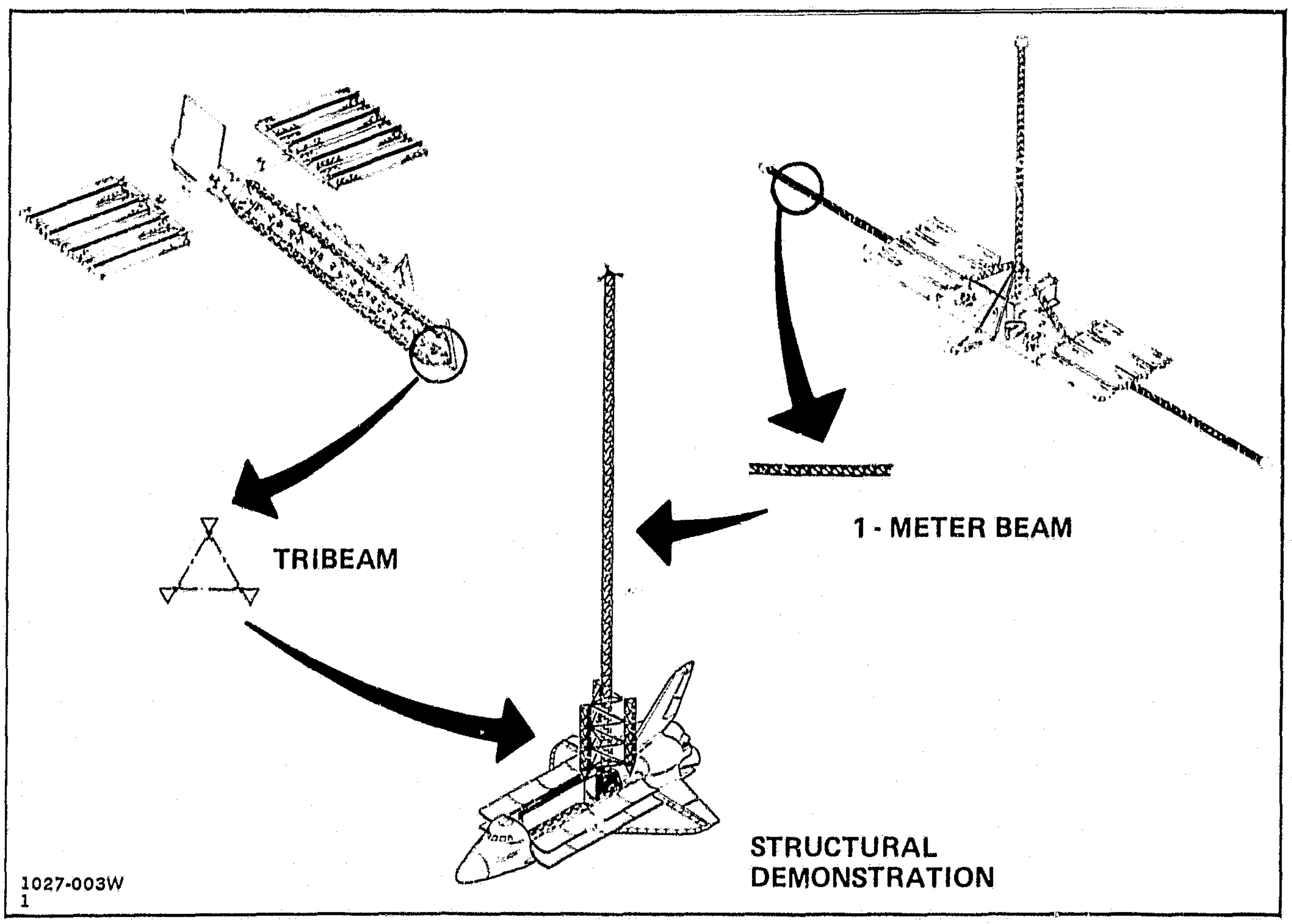

Fig. 3-1 LSS Demo Mission Rationale

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The LSS Platform (Fig. 3-2), has been configured as a simple, free-flyer satellite, capable of supporting low-power payloads as a soil moisture radiometer, and LDEF-type experiments. The long boom provides gravity-gradient stabilization to within ±3° of the local vertical, and because of the low-power nature of the payloads, allows effective use of a modest area of body-mounted solar cells to provide for a mission duration of five years. A baseline altitude of 500 km and 57° orbit inclination has been selected to provide a flight profile for the soil moisture radiometer with an approximate 3 to 4 day revisit over a test area located in the central U.S., and to maximize flight times without altitude reboost. The LDEF-type materials exposure experiments would be serviced per experimenter requirements or during Orbiter reboost intervals assumed to occur about once a year.

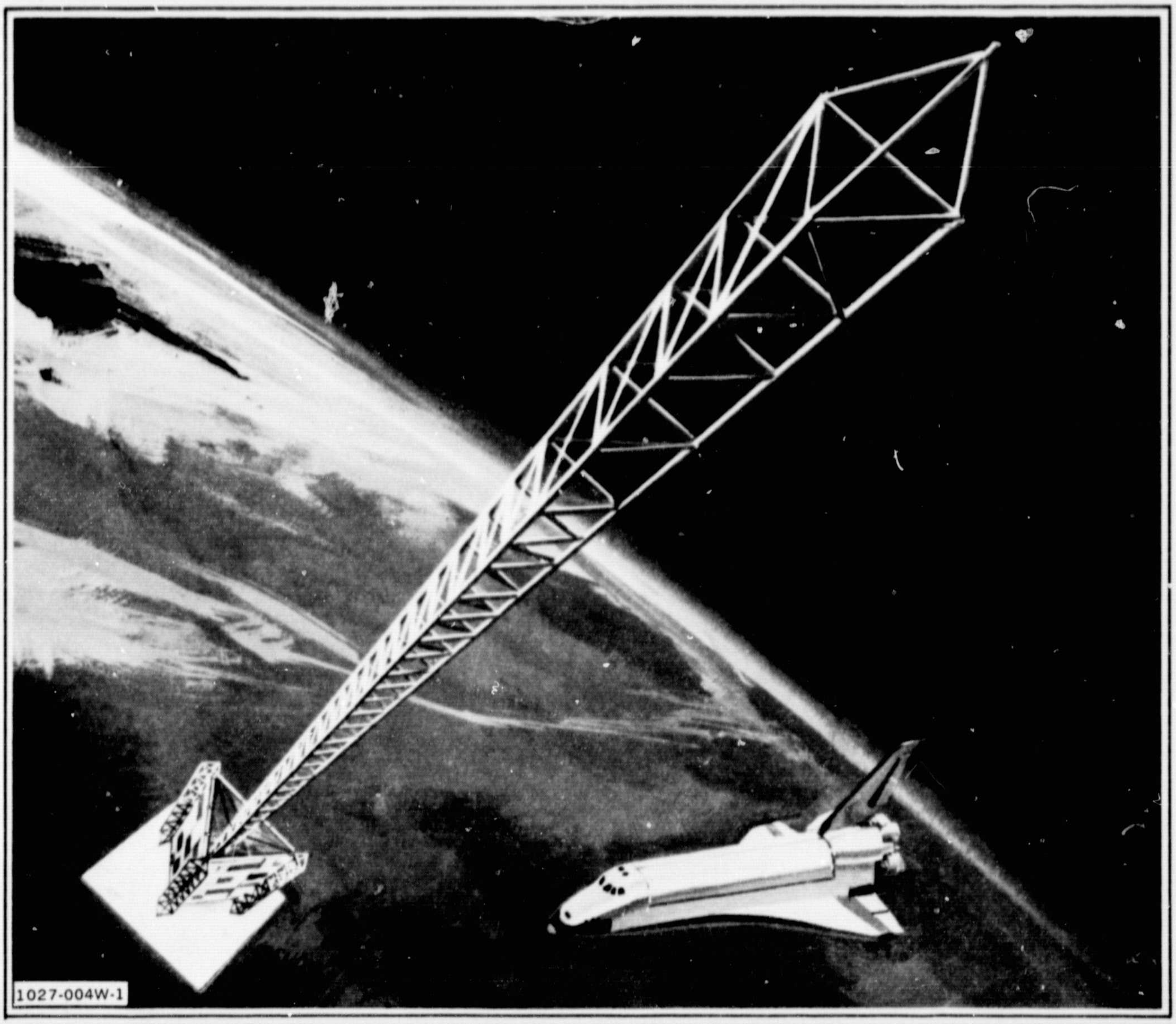

Fig. 3-2 LSS Platform Free-Flier

1

Features of the proposed LSS demonstration mission as they relate to Orbiter utilization, Space Platforms, and overall LSS technology development are shown in Fig. 3-3. The mission represents a viable early Shuttle mission candidate with the ability to support useful mission applications in addition to verifying the ability to assemble ground or space-fabricated large space structures on-orbit. Considerable Orbiter-based construction expertise is acquired, in addition to relevant on-orbit construction, operations, and subsystem/payload integration experience applicable to near-term Space Platforms. Supporting LSS technology development features of the mission cover a broad range of necessary operational and construction-related technology activities relevant to future LSS mission applications. Clearly, this LSS demonstration mission can represent a significant milestone in the development of Large Space Structure capabilities.

FEATURES OF INITIAL MISSION	ORBITER UTILIZATION	SPACE PLATFORMS	LSS TECH DEVELOPMENT
• LOW-COST SHUTTLE MISSION	•		
• LOW-WT EARLY 7-DAY SHUTTLE MISSION CANDIDATE	•	•	•
• SOIL MOISTURE RADIOMETER PAYLOAD RESPONDS TO USER NEED		•	
• COUPLES LDEF EXPERIMENTS "EXPANSION" WITH LSS DEMO	•	•	
• CONSTRUCTION FROM THE ORBITER	•	•	•
• USEABLE ORBIT-BUILT SPACECRAFT	•	•	•
• CONSTRUCTION/ASSEMBLY TECHNIQUES	•	•	•
• LIMITED SUBSYSTEM/PAYLOAD INTEGRATION		•	
• PLUME IMPINGEMENT EVALUATION	•	•	
• BERTHING/SERVICING OPERATIONS	•	•	
• TRIBEAM "STRONGBACK" BASELINE		•	•
• BEAM/BOOM APPLICATIONS		•	•
• LIGHTING EVALUATION	•	•	•
• ASTROWORKER/RMS UTILIZATION	•	•	•
• CONCURRENT VALIDATION OF ABB OPERATIONS	•		•
• ABB/ONE-METER BEAM TESTING	•	•	•
• ON-ORBIT TESTING OF LSS		•	•
• PASSIVE PRECISION GRAV-GRADIENT STABLIZATION		•	•
• TIMELINES VALIDATION VIA NEUTRAL BUOYANCY SIMULATION		•	•
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Fig. 3-3 LSS Platform — Mission Relevance

3.1.2 Mission Definition

The Orbiter is a suitable construction platform for initial development of LSS technology and in-space construction of free-flyer-satellites. Further, to conduct meaningful and effective LSS flight demonstrations using the Orbiter as the construction platform, the general flight control characteristics exhibited by the Orbiter's Vernier RCS (VRCS) have been found desirable. However, it presently appears that insufficient backup/redundancy exists within the VRCS system to allow its use as the primary flight control during an LSS flight demonstration mission. A separate "construction control package" thus appears necessary to allow on-orbit construction, and to avoid undesirable frequency coupling conditions which could occur during both construction and Orbiter/LSS flight operations.

Since lighting considerations for construction favor the use of reflected, diffuse sunlight from the Earth's atmosphere, and on-orbit momentum considerations favor local vertical (LV) orientations, the preferred Orbiter orientations for LSS construction are X-LV and Z-LV, as illustrated in Fig. 3-4.

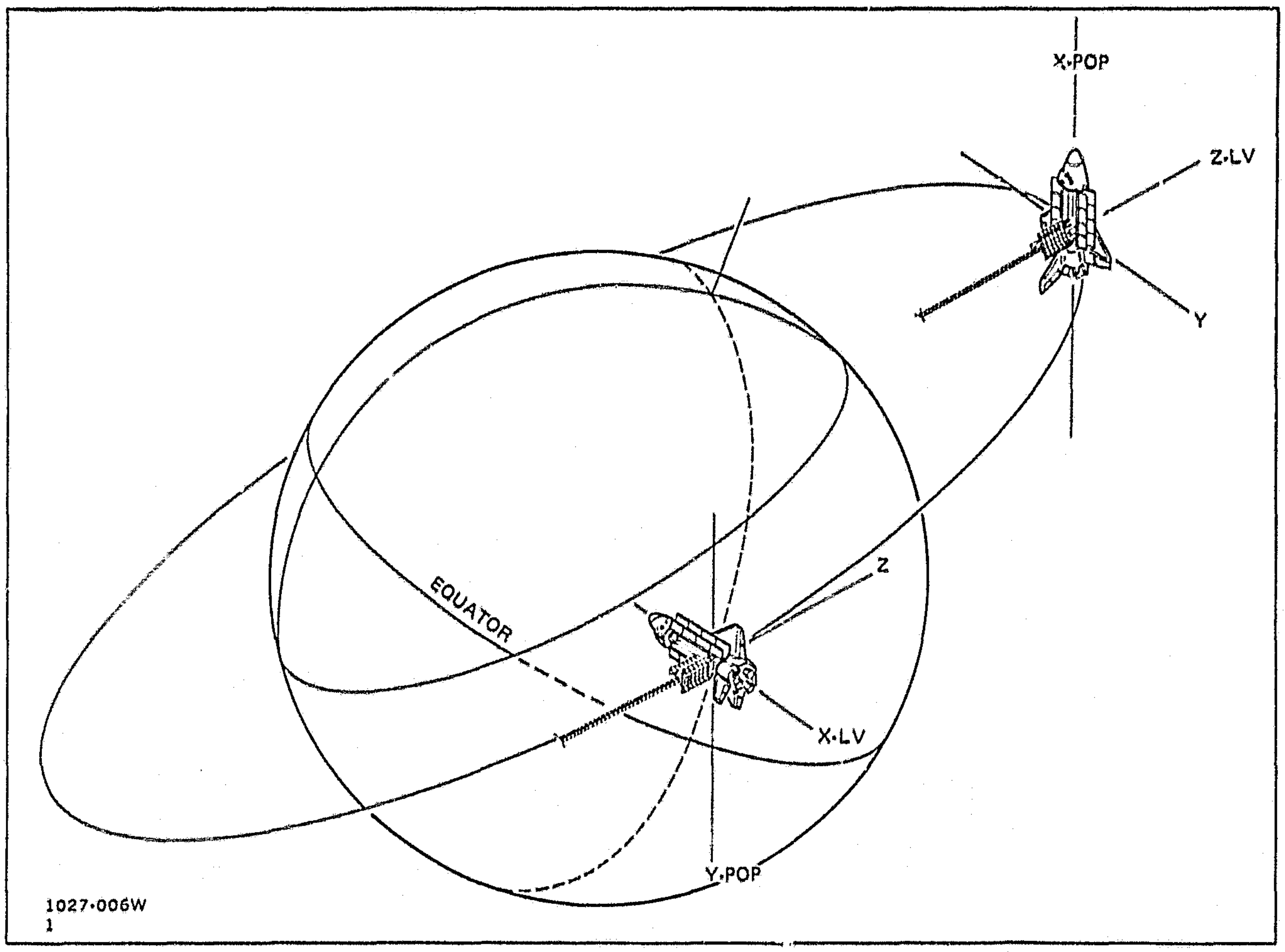

Fig. 3-4 Preferred Orbiter Orientations for LSS Construction

The types of flight tests planned for this mission as illustrated in Fig. 3-5 are:

- Verification of both the Automated Beam Builder's (ABB) operation and the quality of one-meter beam produced
- Determining the structural thermal and dynamic responses of both the one-meter beam and the Tribeam section of the LSS Platform
- Evaluating one-meter beam handling techniques, LSS construction/assembly payload/equipment installation approaches, and operations associated with Platform servicing.

All test objectives can be satisfied within the nominal 7-day Orbiter mission. Capabilities inherent within the Orbiter and its crew of four are sufficient to accomplish the LSS mission with the addition of fuel cell consumables for dark side lighting and an OMS kit for accommodating the baseline altitude/inclination of 500 km/57°. Launch weight is about 19,000 kg vs 21,000 kg allowable for the mission.

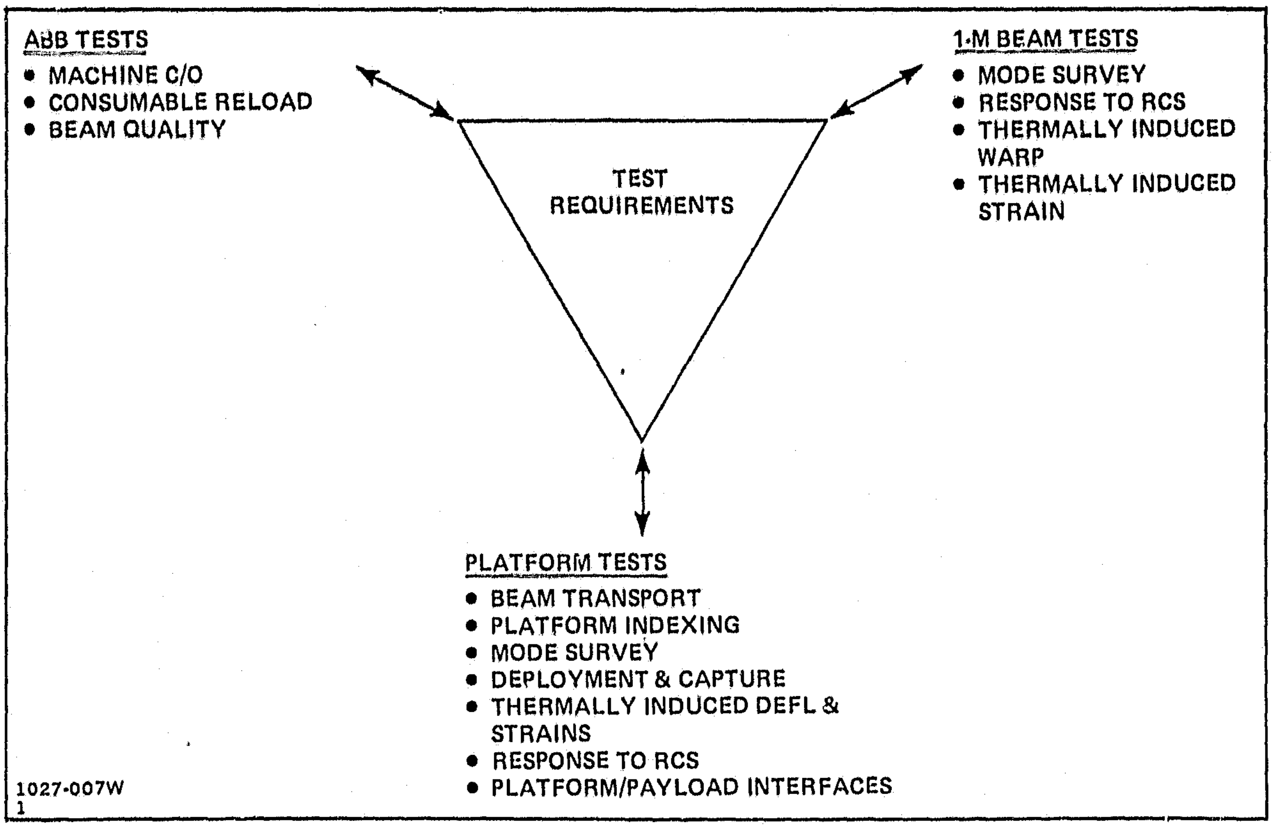

Fig. 3-5 Flight Test Program

The proposed mission activities associated with this 7-day Orbiter flight are illustrated in Fig. 3-6, 3-7 and 3-8.

- Day 2 - Day 1 of the flight is dedicated to launch and space acclimation, thus the direct mission-related activities begin on Day 2. After ABB checkout, a beam is fabricated and stowed for subsequent return to Earth. The final EVA for the day sets up a ground-fabricated/instrumented beam for a test to determine levels of thermally induced strains. A non-EVA work period follows in which the thermal strain test is completed as well as a test designated to determine RMS-induced handling loads on the one-meter beam.

- Day 3 - Day 3 begins with another beam handling test, this one to determine crew-induced loads. Two 10.5-m long beams are fabricated and stowed to be used later in assembly of the LSS free-flier. The final EVA Activity for the day involves fabricating and instrumenting a 40-m length of the satellite's center boom. This beam, while still attached to the ABB, is then checked dimensionally under varying solar conditions and subsequently loaded by firing the Orbiter VRCS.

- Day 4 - The modal survey of the 40-m beam begins mission activities for Day 4. Following this, the center boom is fabricated to its desired length and assembly of the free-flier begins. Approximately half the structural stiffeners are installed before EVA time limitations halt activity for the day.

- Day 5 - The initial mission activity for Day 5 is completion of the stiffener installation which began on Day 4. The remainder of the day is dedicated to non-EVA tests of the free-flier structure. First, the LSS assembly is loaded by the Orbiter VRCS; then its response to thermal conditioning is determined. The last activity of the day is a modal survey of the completed structure.

- Day 6 - Day 6 mission activities are concerned with installing and checking out experiments and the radiometer. While the structural assembly is still attached to the ABB, the folded radiometer is fastened to the platform. The LSS is then repositioned across the payload bay where radiometer deployment takes place and experiment/subsystem racks are installed. This ends the EVA for the day and is followed by a radiometer checkout.

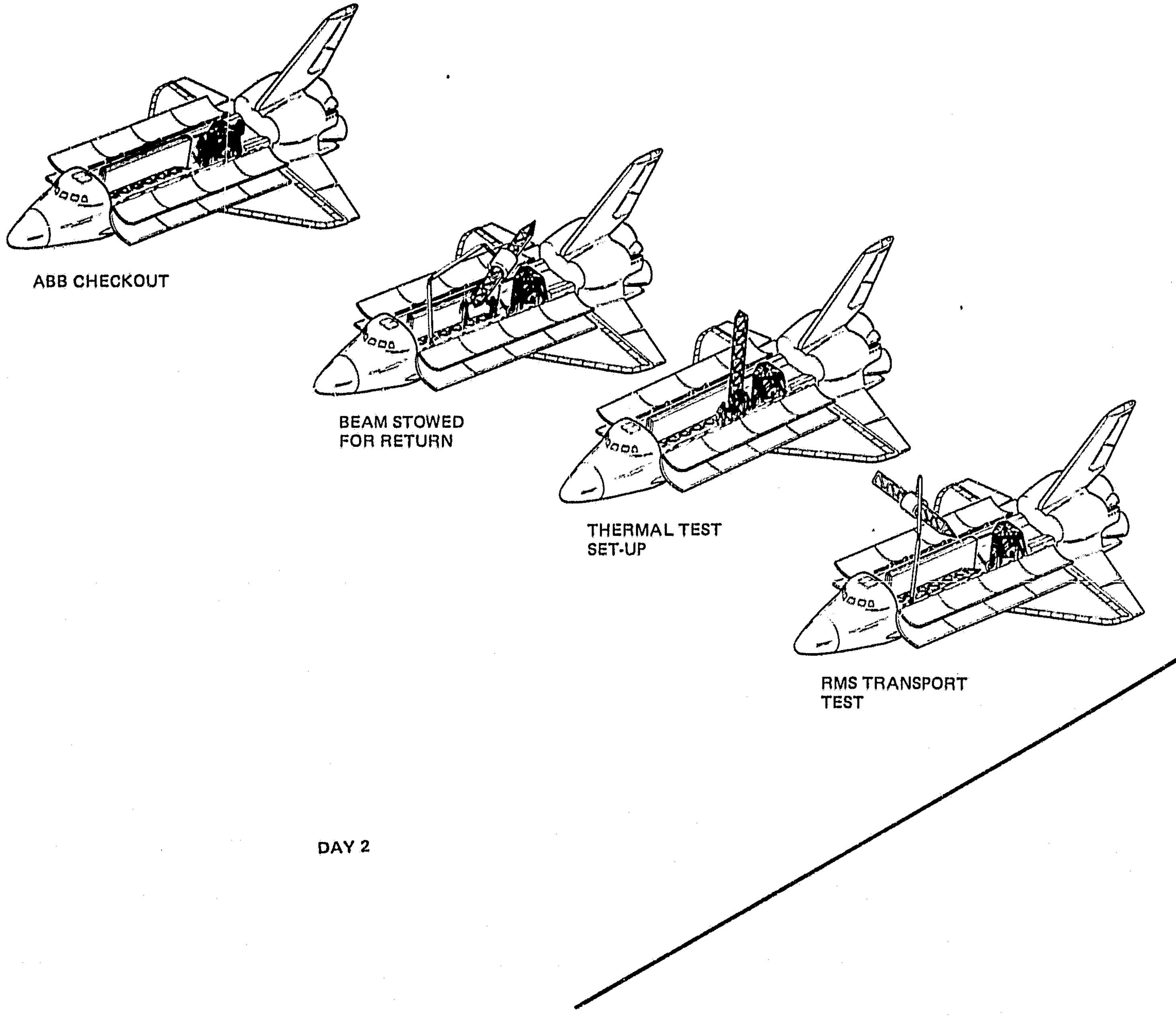
ABB CHECKOUT
BEAM STOWED FOR RETURN
THERMAL TEST SET-UP
RMS TRANSPORT TEST
DAY 2

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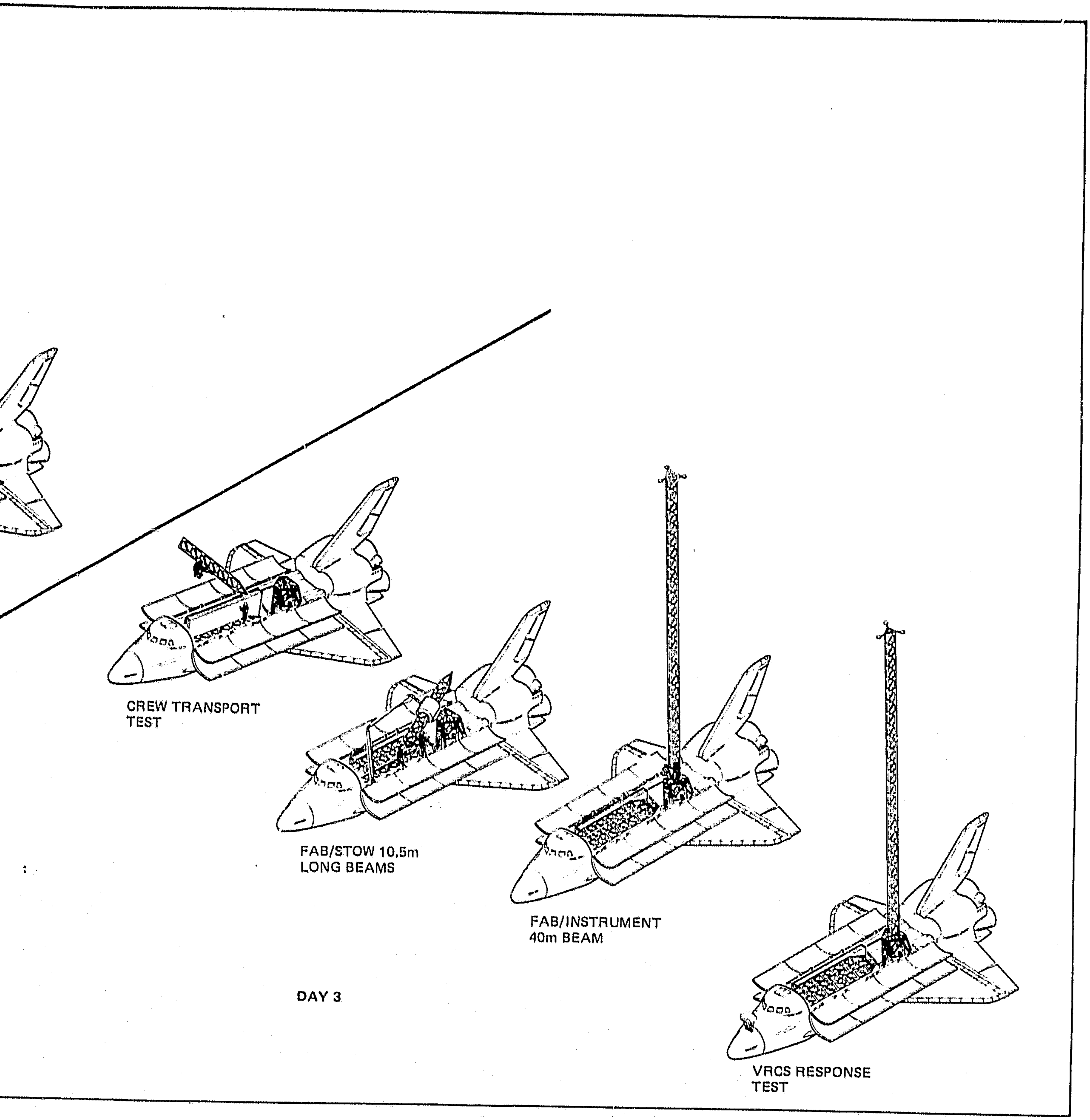
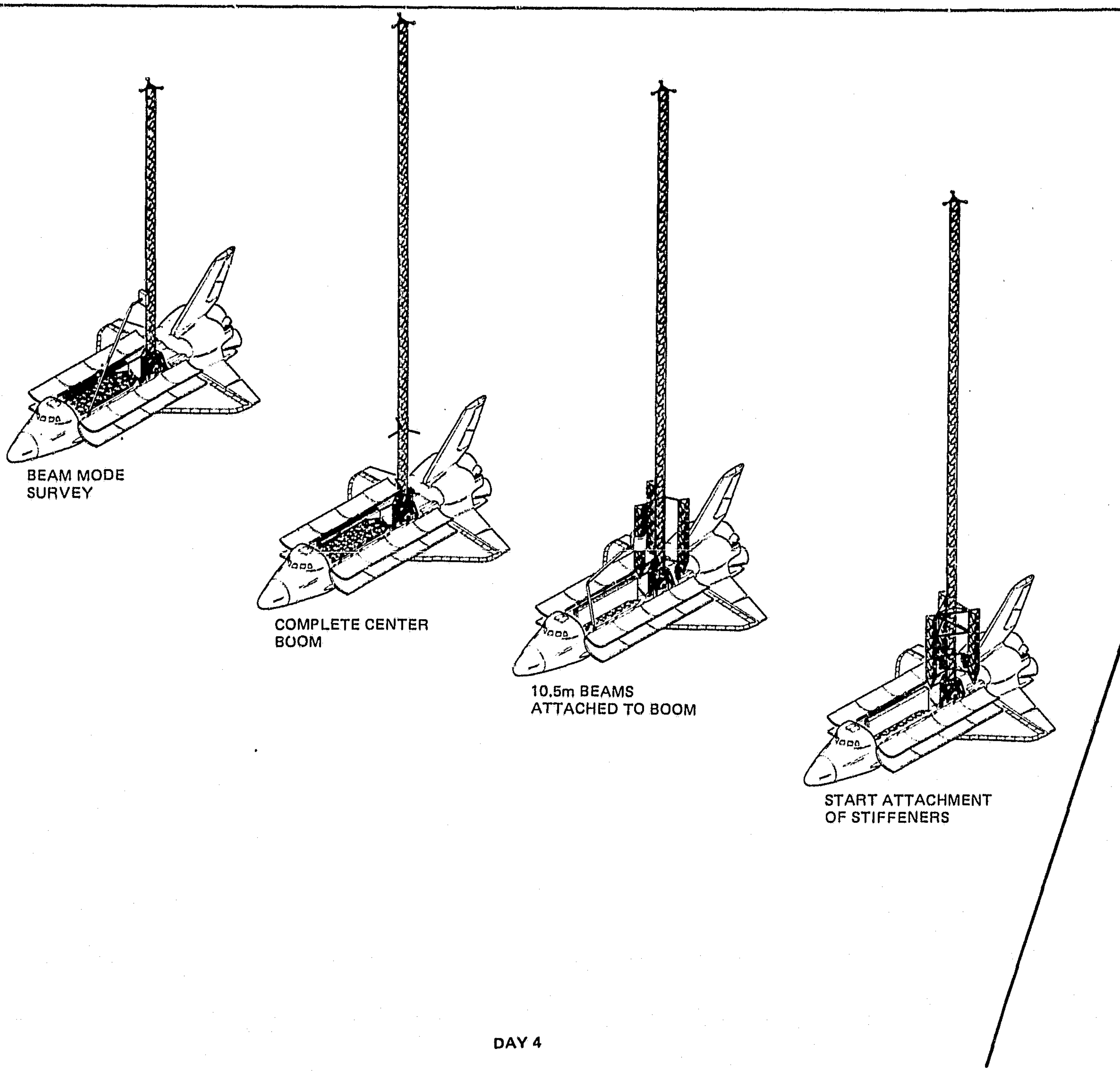


Fig. 3-6 Mission Activity – Day 2 and 3



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FOLDOUT FRAME

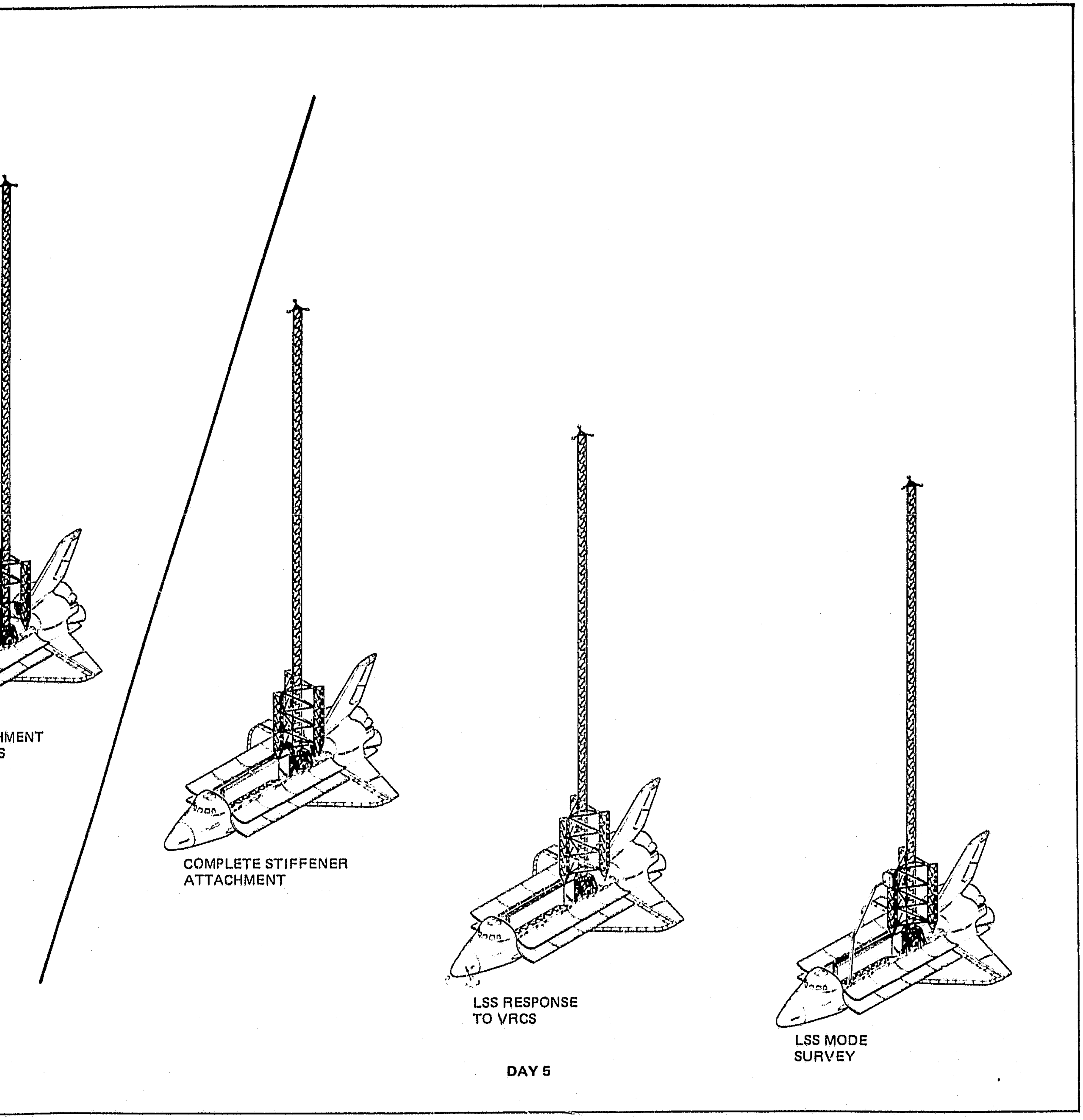
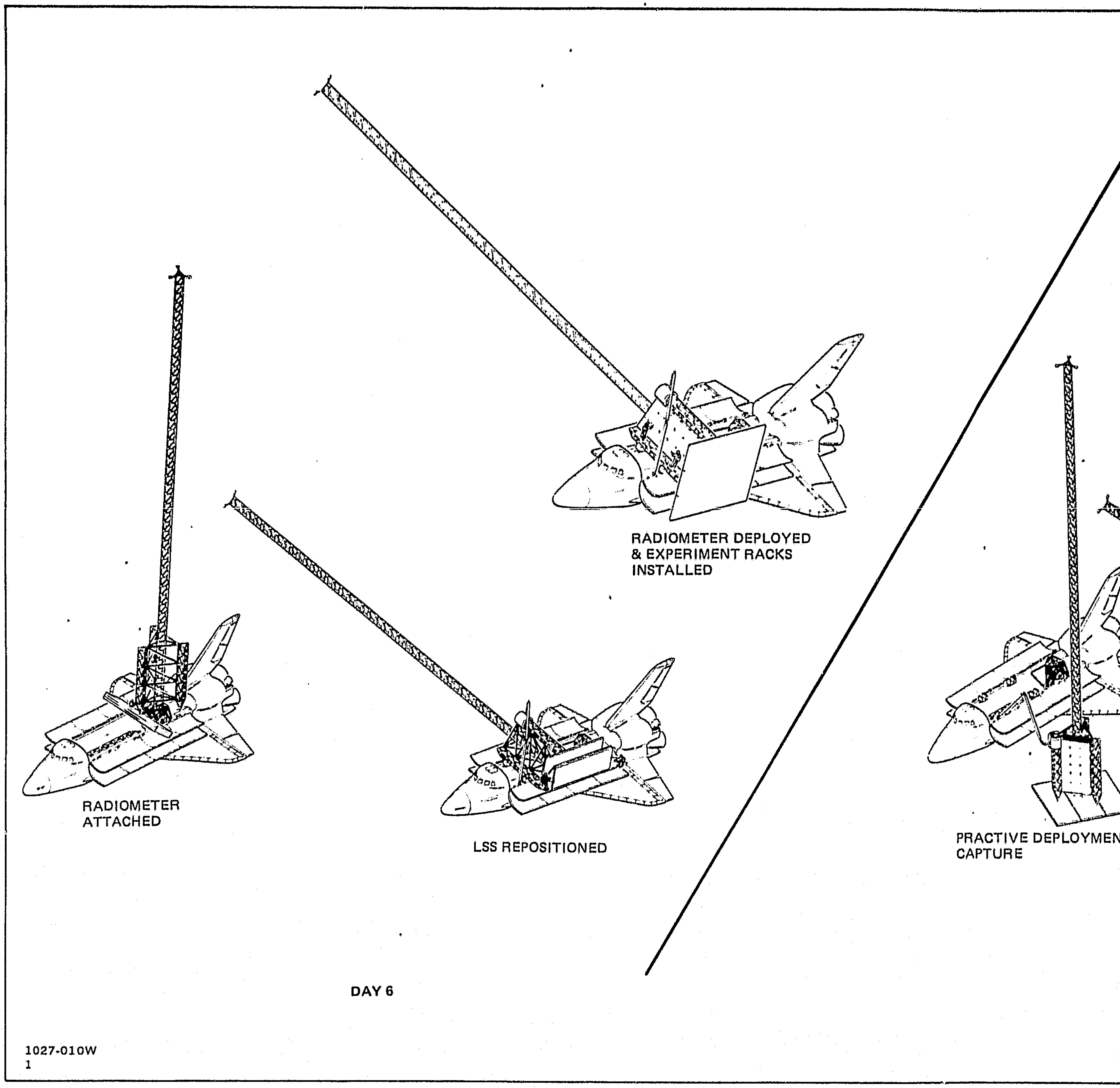


Fig. 3-7 Mission Activity – Day 4 and 5


RADIOMETER DEPLOYED
& EXPERIMENT RACKS
INSTALLED
RADIOMETER
ATTACHED
LSS REPOSITIONED
PRACTIVE DEPLOYMEN
CAPTURE
DAY 6
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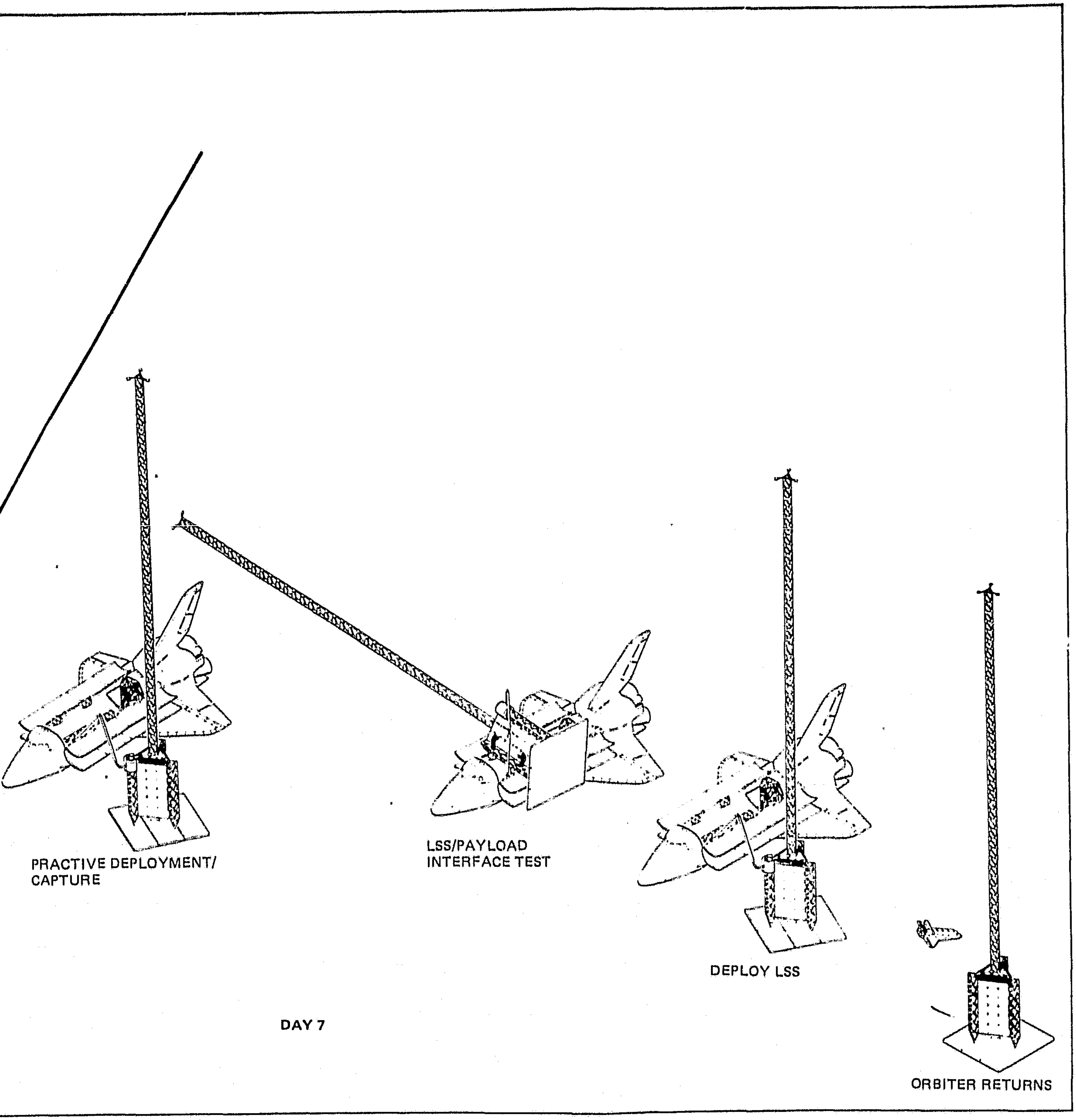

Fig. 3-8 Mission Acitivity – Day 6 and 7

- Day 7 - Activities on Day 7 begin with a practice LSS deployment, capture and berthing operation using the Orbiter RMS. After berthing the LSS, a payload interface test is conducted to demonstrate servicing operations. The free-flier is then deployed and Orbiter de-orbit preparations begin.

3.1.3 Programmatics

A nominal LSS demonstration mission schedule is about 2 1/2 to 3 years following ATP. Thus, an FY 81 start could culminate in a demonstration flight in the 1983-1984 time-period. Principal schedule drivers are: Systems Engineering and Integration, Simulation and Crew Training, and ABB Modification to flight status.

Program costs for the LSS Platform free-flyer are shown in Fig. 3-9. Estimated costs for a combined ABB verification and LSS demonstration mission are about $24 million exclusive of Shuttle launch costs, and includes adaptation of the ground demonstration ABB to flight status.

WBS	COST ITEM	$M 1979
1.1	PROJECT MANAGEMENT	0.85
1.2	SYS ENGR & INTEG	1.74
1.3	SYSTEMS GROUND TEST	1.47
1.4	GSE	0.26
1.5	DEMO ARTICLE	0.78
1.6	ASSEM SUPPORT EQUIP.	1.77
1.7	LOGISTICS	0.23
1.8	GROUND OPS	0.17
1.9	FLIGHT OPS	0.28
	CONTINGENCY (25%)	1.89
1.0	SUBTOTAL	9.44
2.1	SHUTTLE SUPPORT*	24.22
2.2	ABB	9.5
2.0	SUBTOTAL	33.72
3.1	SUBSYSTEMS	3.75
	RADIOMETER	—
	CONTINGENCY (25%)	0.94
	SUBTOTAL	4.69
	PROGRAM TOTAL	47.85

* SHUTTLE COST + EPS + OMS KIT
• ALL COSTS ARE IN MILLIONS OF 1979 DOLLARS

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Fig. 3-9 Cost Breakdown — LSS Platform Free-Flier Option.

Figure 3-10 compares the Structural Demonstrator and free-flier Platform costs generated for the LSS concepts developed in both initial and follow-on study efforts. Structural Demonstrator costs are similar, whereas the more than $20M reduction in free-flyer Platform costs reflects a considerable simplification in subsystems complexity for the presently-proposed LSS platform.

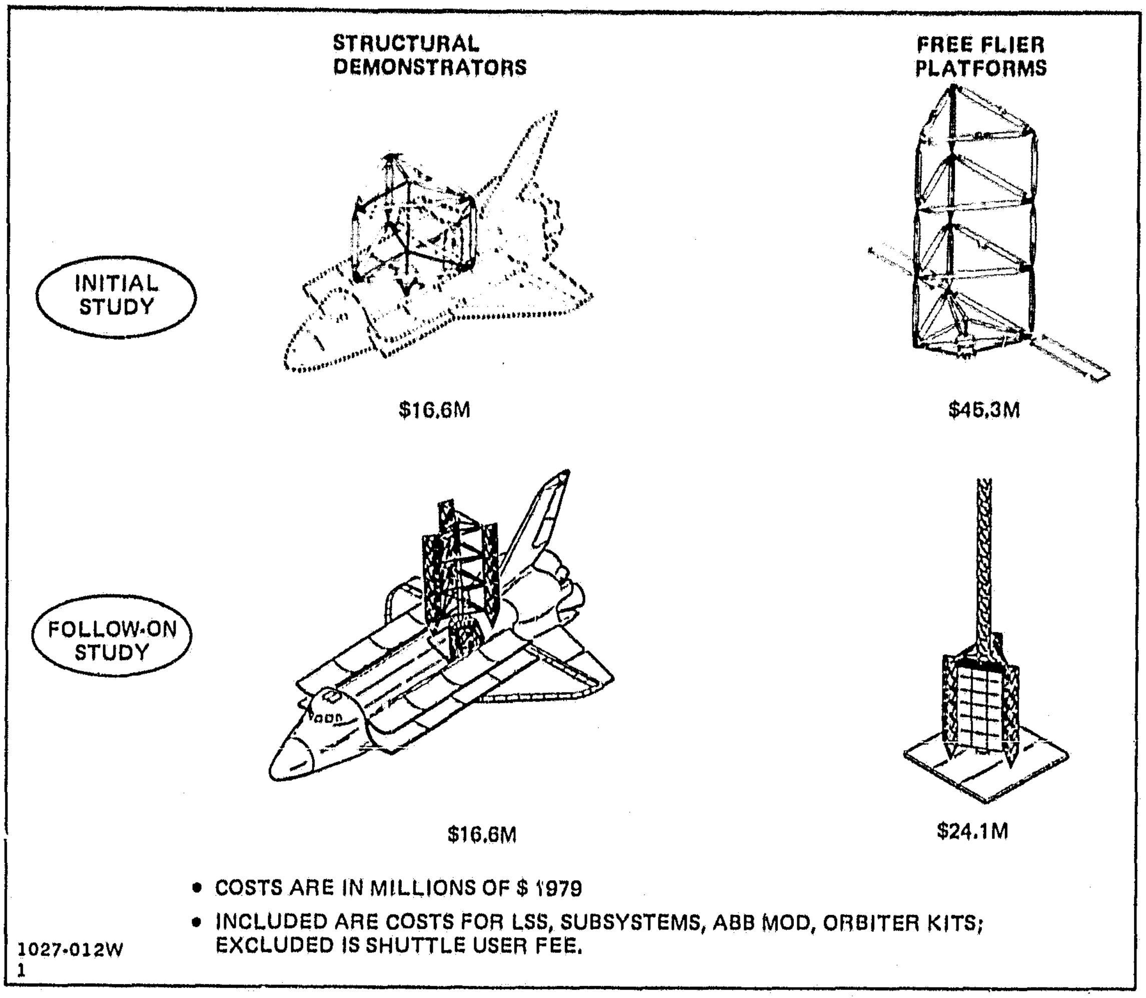

Fig. 3-10 LSS Concepts Cost Comparison

3.1.4 Supporting Analyses

3.1.4.1 Construction Limitations - An investigation of construction limitations associated with large space structures constructed from the Orbiter or other earth-orbiting construction platforms was conducted. The analysis identified potential length restrictions imposed on a 1-meter beam and varing depth Tribeams by flight control and dynamic frequency coupling considerations. One-meter beam and Tribeam frequencies as a function of length are shown in Fig. 3-11. Since specific Orbiter inertia characteristics are only important for the intermediate length beams, the data shown is valid for typical earth-orbiting construction platforms as well as the Orbiter, in the higher and lower beam length ranges. Both LEO and GEO limiting control frequencies have been superimposed on the curves, and the appropriate frequency separation factors that could apply, to illustrate the maximum controllable beam lengths in these orbits.

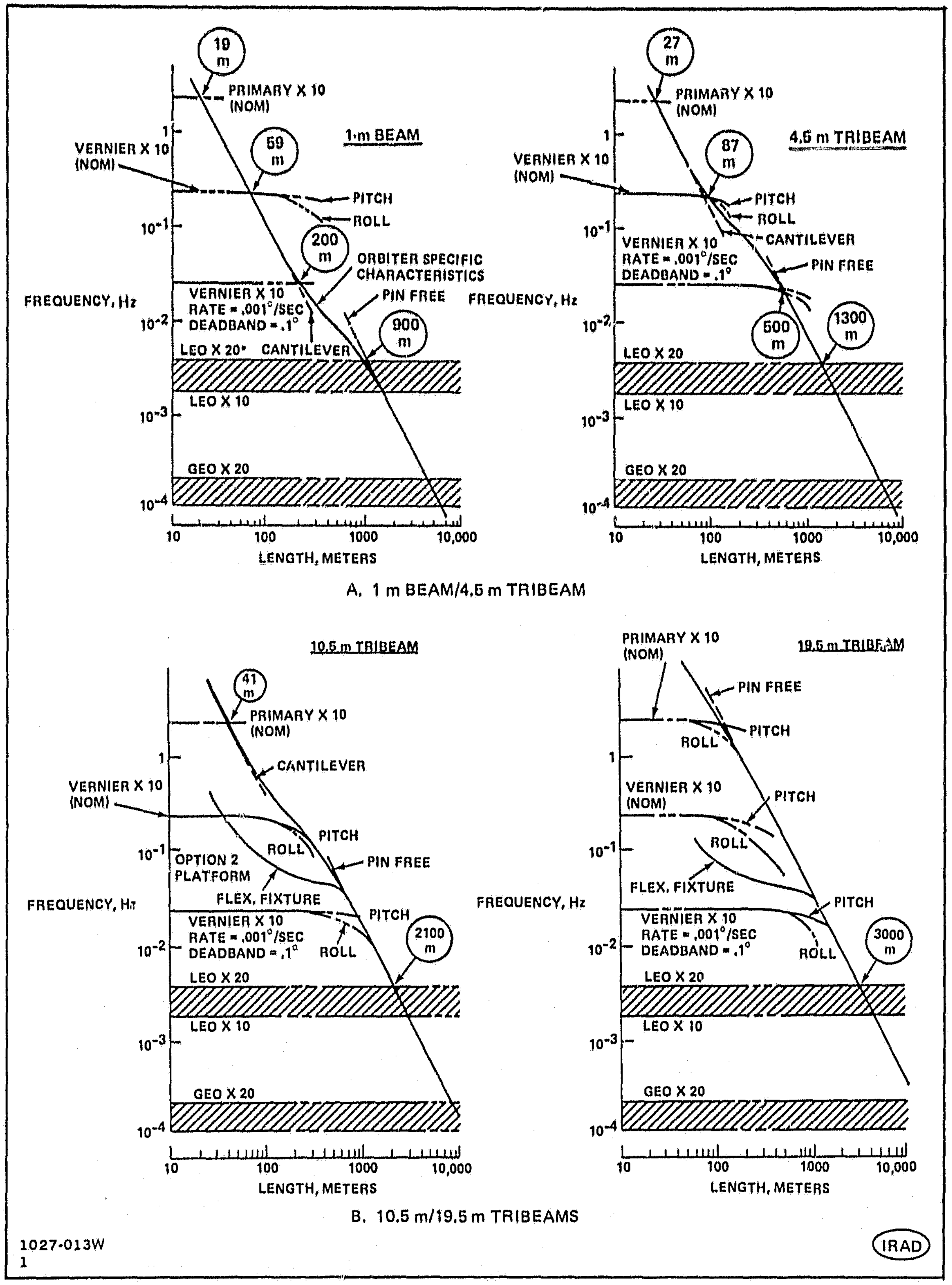

Fig. 3-11 LSS Construction Limitations

The analysis has indicated the following:

- Maximum 1-meter beam lengths under Primary and Vernier RCS operations are 19 m and 59 m, respectively.
- Maximum LSS lengths are primarily limited by structural frequency and frequency coupling considerations rather than strength limitations.
- Variations in control parameters (deadband, limit cycle rate) can be employed to permit construction of longer beam lengths.
- Fixture flexibility must be considered to avoid control frequency coupling. Although for very long beam lengths (>1000 m), fixture flexibility effects are no longer dominant, passage through this shorter length regime is necessary to attain these lengths
- Maximum length structures are limited by orbital rate and appropriate frequency separation factors.
- The longest possible structures in LEO could be built with construction platform control systems exhibiting limit cycle rates of 0.001°/sec or less and deadband angle ranges of between 0.2 and 0.6 deg.
- Composites will allow slightly longer beam lengths to be constructed (~20-30%) because of the resulting higher stiffness to mass ratio relative to aluminum.

3.1.4.2 Thermal Analyses - A detailed transient analysis of a 1-meter beam was performed, which includes consideration of caps, verticals, and diagonals and the effects of blockage during an orbit transit. Our investigations indicate that steady-state thermal analyses are inadequate for evaluating alternate thermal coatings or structural response of LSS in orbit. Transient thermal analyses reflecting blockage/shadowing of structural elements, during an orbit, are necessary.

As illustrated in Fig. 3-12 and 3-13, considerations of blockage/shadowing, and minimization of temperature gradients between structural elements of a 1-meter beam, favor the use of Alzak or white paint coatings. With these types of coatings, a 1-meter beam's structural response in orbit, in terms of twist (for example) appear to be similar to the manufacturing tolerances expected for comparable length beams. The twist induced into a 1-meter aluminum beam by orbital conditions, is minimal and not expected to pose near-term construction problems.

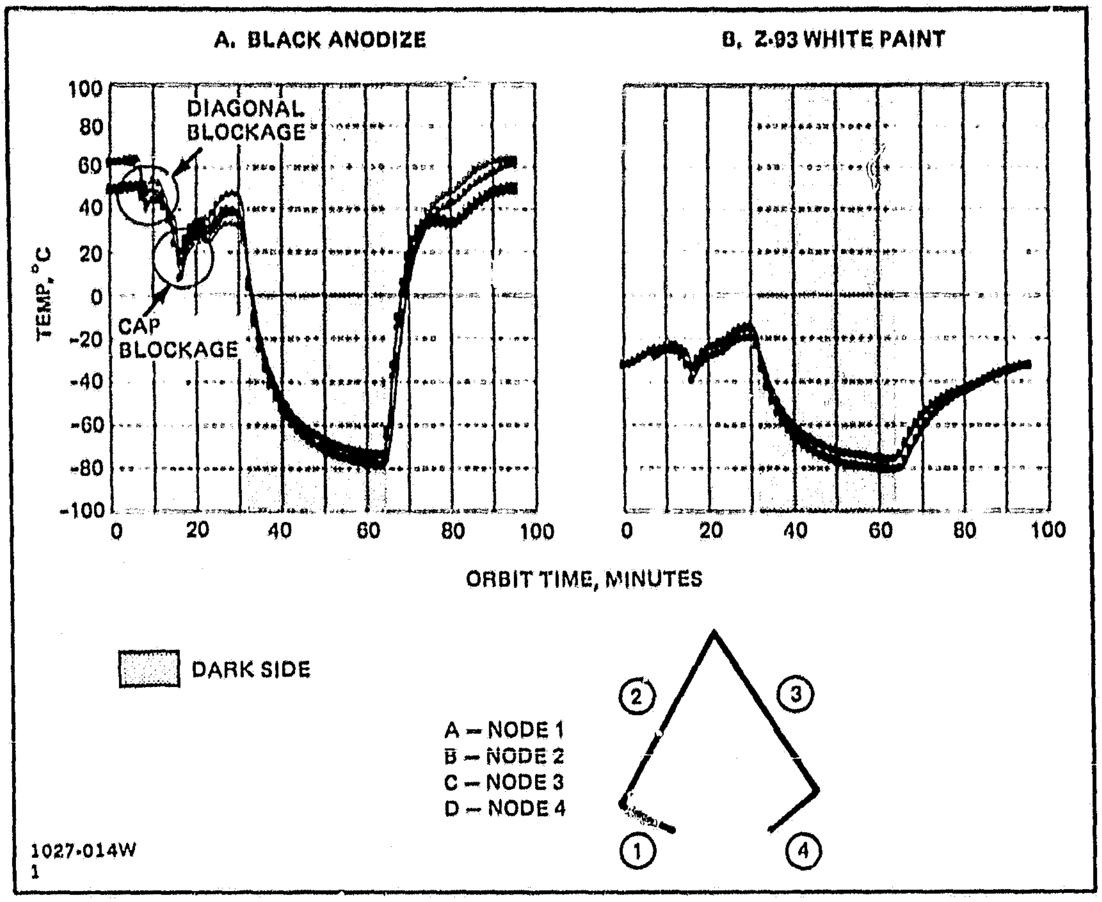

Fig. 3-12 One-Meter Beam Cap — Coatings Comparison

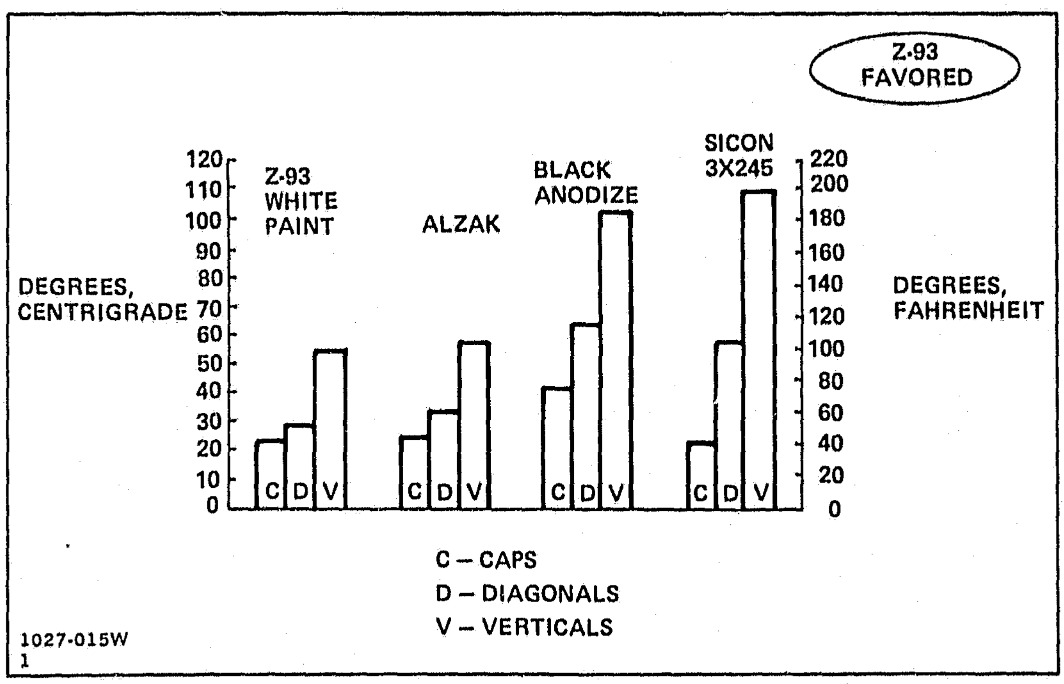

Fig. 3-13 Peak Temperature Differences Between Structural Elements

Analyses of hybrid material combinations of 1-meter beam elements (Fig. 3-14) involving the use of composite verticals and diagonals, indicate that distortions during an orbit are increased over those experienced by all-aluminum or all-composite beam structures. The use of mixed materials in primary LSS structures, therefore, should be carefully considered for their respective applications.

The linear motions and distortions of a beam are fundamental design considerations which must be reflected in joint designs, construction/assembly procedures, and operation of LSS. The structure's response to the orbit environment in terms of distortion and displacement, coupled with manufacturing tolerances associated with fabrication of the basic structure, establish a condition which is "equivalent" to built-in prestresses within a structure. Above this base condition, the applied loads must be considered for each LSS application.

Our analyses indicate that the structural response of a single 1-meter beam "building block", in a worst case orientation, should adequately describe the limiting thermal design conditions of an LSS composed of multiple "building block" elements. However, the transient temperature characteristics of the "building block" structures, and their structural elements, are necessary to determine the distortion of an LSS in orbit. The blockage effects of payloads, subsystems, etc. mounted to an LSS, also represent special cases requiring detailed analysis for each mission application.

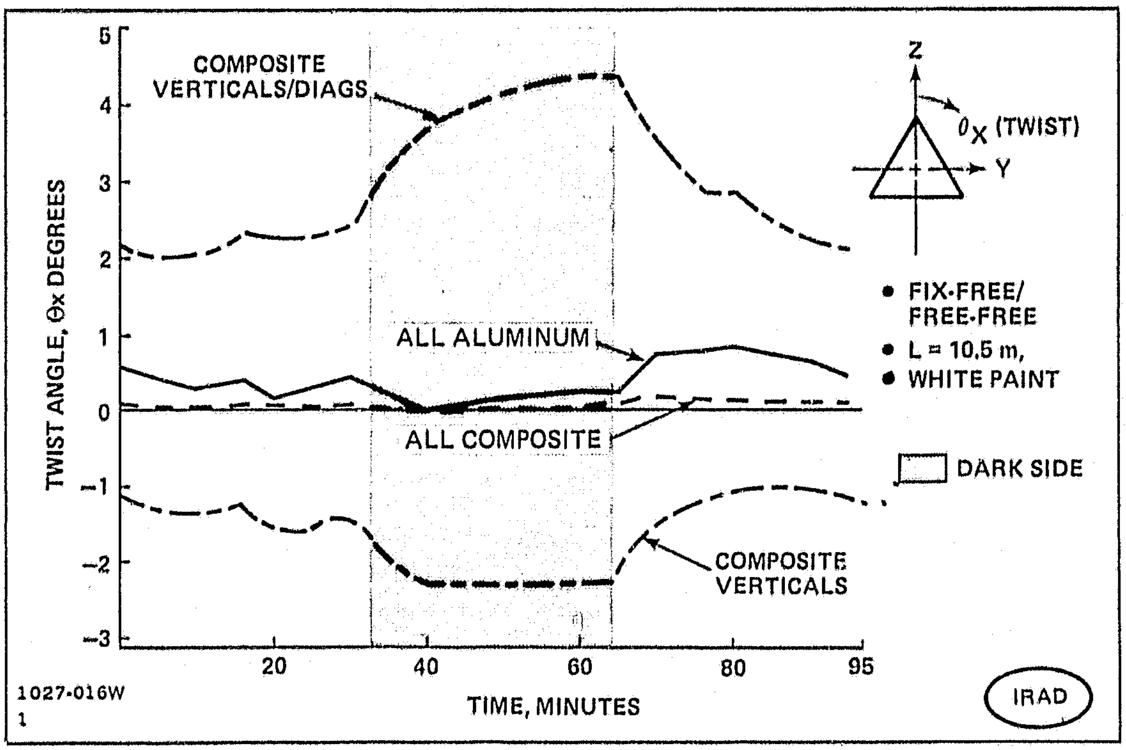

Fig. 3-14 One-Meter Beam Twist During an Orbit

3.2 RECOMMENDATIONS

The Astroworker-erected, space fabricated, free-flying LSS Platform identified in this study, is a viable, low-cost, low-risk approach for an early LSS flight demonstration mission with relevance to both near-term Space Platforms and overall LSS technology development. Its consideration as an early Shuttle mission candidate is recommended.

To conduct LSS construction missions from the Orbiter, the general control capabilities of the VRCS are necessary. However, since there are apparent operational limitations associated with the VRCS, it is recommended that a seperate "construction control package" be investigated to enable LSS construction missions to be effectively performed using the Orbiter as the construction platform. The control package should be designed to allow on-orbit construction of LSS, and to avoid undesirable frequency coupling conditions which could occur during an Orbiter/LSS mission.

Supporting technology development efforts are also recommended relating to thermal vacuum tests of a 1-meter beam, and further study/development of a clamshell RMS end-effector should be initiated (Fig. 3-15). In addition, the detail design of joints associated with the LSS demo Tribeam should be initiated, and the joint designs evaluated in neutral buoyancy facilities in order to begin the process of establishing relevent construction/assembly timelines. It is also recommended that a neutral buoyancy program be implemented, specifically focused toward this LSS demonstration mission.

Additional simulation efforts are recommended to establish the maximum practical EVA-time that can effectively be utilized for an Orbiter-based LSS mission. Although a six-hour EVA limitation is presently believed to be acceptable, and has been used for mission planning purposes, the reality and effectiveness of this extended EVA duration remains to be verified.

Simulation efforts are also needed to evaluate lighting requirements for dark-side construction/assembly operations and Astroworker effectiveness in EVA operations. Both free-floating (tethered and RMU) and restrained (cherry picker/RMS) construction modes should be evaluated, together with the potential area vs task lighting needs associated with these candidate modes of Astroworker construction.

A key output of this study has been the subject of LSS construction limitations both from the Orbiter and future space construction platforms. Limitations concerning

maximum length structures, frequency coupling, and construction platform control requirements allowing broad construction latitude have been identified analytically. Verification of these limitations should be a major objective of initial LSS technology flights.

Our present LSS mission planning has baselined a flight adaption of the ground demonstration ABB machine. This flight version is estimated to weigh about 7250 kg (16,000 lb). Studies of flight weight ABB designs, reflecting ABB ground demonstration experience, are recommended to establish the necessary design characteristics of these machines and to provide appropriate weight "bogeys" for operational (versus

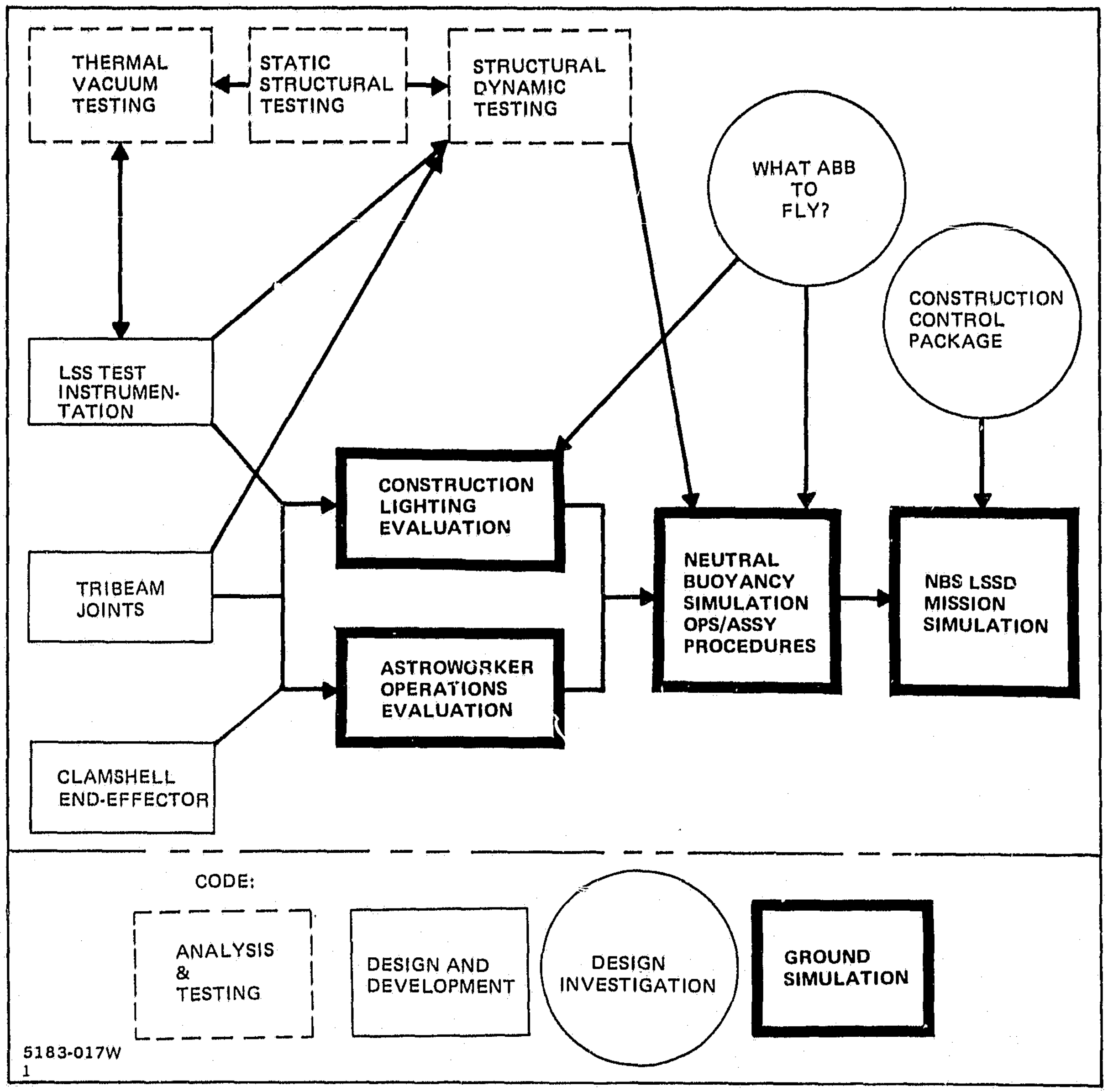

Fig. 3-15 Supporting Research and Technology Development

demonstration) ABB hardware. Of critical importance to this LSS demonstration mission is a realistic appraisal of the practicality/cost-effectiveness of flying a modified ground demonstration ABB. This appraisal and its subsequent consequences represent the "long-pole-in-the-tent" vis-a-vis this LSS flight demonstration mission. An early appraisal, therefore, addressing the issue of "what ABB to fly?" is urgently recommended. As expressed previously, the low-cost/low risk aspects of this proposed LSS mission offer considerable appeal . . .the ABB issue must be resolved expeditiously.